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Failure Cause Analysis of Pole Transformers

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Abstract - This paper describes the symptoms with the failure causes of pole transformers analyzed at KEPCO branch offices' request in 2001, and ultimately aims for devising proper countermeasures against the failures. The failure causes are generally divided into problems in manufacturing, mounting and operating. The pole transformers encounter the failure with unique mechanisms. To verify the mechanisms to failures and help devise proper countermeasures, a flowchart is proposed based on the authors' experience and foreign case studies. The failure causes of pole transformers can be analyzed more exactly by using the flowchart.

1. Introduction

As of December, 2000, the number of the pole transformers mounted and operated in this country was over 1,280,000, and most of the transformers has been replaced every year by the damage due to the various kinds of causes[1]. However, it is, actually, very difficult for KEPCO branch offices to find out the exact failure causes. There are many reasons; insufficient data/information applicable to practical analysis compared with power transformers; non-systematization of analytical methods; lack of understanding of expert system constructed by experts' know-how. Therefore, this paper is ultimately aimed at the preparation of the countermeasures against the recurrence of pole transformer failures, based on the authors' experience, case studies carried out abroad, researchers and officials in charge with KEPCO. The results will be helpful to the KEPCO branch officials and pole transformer manufacturers.

2. Failure of Pole Transformer

2.1 Factors affecting pole transformer failure

2.1.1 Problems in manufacturing

a. poor impregnation in varnish

Unexpectedly, failures due to poor impregnation in varnish frequently occur, and the causes are as follows;

- voids or impurities in process of impregnation under vacuum
- imperfect hardening due to impregnation in insulating oil before complete dry of varnish
- imperfect permeation of varnish between coils due to impregnation in too strong varnish

For the causes above, voids are created between coils and varnish, which concentrates the electric field around the voids, therefore, they act as a factor causing partial discharges and electrical breakdown in the primary winding. In addition, the varnish flows down and hardens in process of dry, which closes up the oil ducts to interrupt the circulation of insulating oil. The processes make the pole transformers have the hottest spot to reduce the insulating performance of the pole transformers.

b. poor winding

The deformation of the windings is more severe because of poor winding, and main factors of failure are as follows;

- spaces between turns
- unbalanced windings between layers
- double windings on a turn

When a space exists between turns of the conductors wound on the insulating paper between layers, the conductors moves with the frequency twice commercial frequency because of the electromagnetic forces. If the movement is continued, mechanical fatigue is accumulated on the insulating materials to cause the failure. However, as a result of the teardown of the pole transformers more than 100 at KEPCO branches' request to clear up the failure causes of the pole transformers in 2001, several of the pole transformer failures were caused by the broken primary conductor at medium or inner layers. In this case, it was concluded that the poor insulation between layers or the permeation of water and foreign particles resulted in the failure.

c. elbow-shaped bend due to solid split bars

In process of winding, solid split bars or corrugated pressboards are inserted every 3 or 4 layers to improve the cooling efficiency by circulating insulating oil. An elbow-shaped bend is made because of a structural problem when solid split bars are employed, and the angle of the elbow-shaped bend is sharpened by;

- winding with excessive force on solid split bars
- winding not taking curvature at curved points into account

When the conductors are wound like above, there can be an elbow-shaped bend on solid split bars, which ultimately causes partial discharges or breakdown since electrical stress increases at the triple junction at which different materials meet.

d. poor gasket
For perfect sealing, proper force has to be applied lest the gaps between high voltage terminal and the top surface of the high voltage bushing should exist, the causes below drive the pole transformers to failure.

- poor material of gasket
- imperfect sealing
- breakage of bushings due to excessive tightening force

The poor gasket causes rather the permeation of water than the failure of the pole transformers.

e. poor welding of tank
Poor welding mainly leads to the permeation of the water and the leakage of the insulating oil.

2.1.2 Problems in mounting

a. breakage of high/low voltage bushings
The breakage of the high/low voltage bushings is due to:

- damage or cracks due to external impact or careless handling
- reduction in hardness due to poor materials

The causes mentioned above result in the permeation of water or the leakage of insulating oil.

b. poor relief valve
The relief valve is designed to automatically work and release the internal pressure when its rise reaches $0.7\pm0.14[kg/cm^2]$, and go to the fault with following causes.

- pull ring axis bending due to careless handling
- loose bolt due to poor assembly in manufacturing

The poor relief valve often causes the permeation of water or the leakage of insulating oil.

c. bad restoration to original state after voltage regulation
Unless the handhole is not completely sealed after adjusting the tap changer to compensate the voltage of distribution line end, the permeation of water and the leakage of insulating oil are expected.

2.1.3 Problems in operating

a. operation under overload
When the pole transformers are operated for long under overload condition, the internal insulating materials are aged by the temperature rise and the leakage current, etc. Since the insulating materials are carbonized and the leakage current increases, the ageing is accelerated and the insulating performance is getting worse to be short circuit failure due to internal arc. The arc energy generated at the arc decomposes the insulating oil into combustible gases[2]. The internal pressure rapidly increases because of the generated gases, which has the insulating oil blown out or the pole transformer exploded[3].

b. primary/secondary surges
The primary surge results in the breakage of the high voltage bushing, the arc between the cover and the high voltage bushing terminal and the breaking down of the primary conductors in the outer layer, while the secondary surge does the breaking down of the primary conductors in the inner/medium layer and secondary conductors and carbonization of the adjacent insulating materials[4].

c. secular ageing
The life of the pole transformer is generally known as about 13 years, but it is actually used for more than 20 years in this country. The secular ageing of pole transformers can be distinguished by the discoloration degree, the dissipation factor and the spectrophotometry of the insulating oil, but very difficult.

2.2 Developing mechanisms by failure causes

The failure causes of pole transformers are typically divided into: thermal ageing due to overload and high temperature operation, reduction in dielectric strength due to water permeation, short time ageing due to internal/external surge voltage/current, ageing due to discharge and mechanical damage/ageing, etc. The increase of the combustible gases and the leakage current and accumulated fatigue due to the ageing finally lead the pole transformers to breakdown[3].

2.2.1 Thermal ageing

Thermal ageing is divided into thermal depolymerization and thermal oxidation.

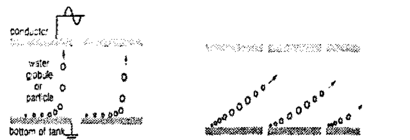
- thermal depolymerization
The molecular chains of insulating material are cut by heat, and the cutting is main sources of thermal ageing known as pyrolysis, thermal dissociation and depolymerization. The combustible gases are generated by the source generating local heat in the insulating oil. The gases exponentially increases with temperature. Hydrogen(H_2) and acetylene(C_2H_2) are mainly generated over 1,000[℃], and propyiene(C_3H_3), ethylene(C_2H_4) and methane(CH_4) below 1,000 [℃]. Thanks to the characteristics, the temperature of the hot spots and the amount of the generated gases can be expected by gas analysis[8].

- thermal oxidation(oxidative ageing)
The molecular chains are separated by the reaction of the insulating materials on the ambient oxygen-thermal oxidation. Thermal depolymerization is cut by the reaction on the environmental materials, while thermal oxidation needs oxygen to be cut. Thermal

oxidation can be progressed by automatic oxidation below 0[℃], as well as at high temperature. The basic consumption of oxygen increases the reaction speed of thermal oxidation. Since the reaction is exponentially governed by the temperature, ambient moisture, metal, the life of the insulating materials exponentially decreases based on the Arrhenius equation.

2.2.2 Reduction of dielectric strength due to water permeation

With showing the mechanism below, the water globules permeating into the pole transformers cause the failure of pole transformers.



(a) field strength 0 kV/㎜ (b) field strength 3 kV/㎜

(c) field strength 6 kV/㎜ (d) field strength 10 kV/㎜ (e) field strength 16 kV/㎜

Fig.1 Breakdown mechanism due to instability of water globule on tank bottom

As shown in Fig. 1, as the field strength increases, the water globules on the tank bottom are arranged in the direction of the field to ultimately bridge between the conductor and the tank[7].

2.2.3 Thermal ageing within short time due to internal/external surge voltage/current

Surge voltage/current generated by internal/external causes of pole transformers gives rise to a short time failure, and the surge is mainly due to: lightning or switching impulse voltages via primary/secondary side of pole transformers; internal short circuit current due to the breakdown of the insulating materials; external short circuit current on load side. Out of the causes, as the last is explained in many references, the failure mechanisms due to former 2 causes are illustrated in this paper. To explain the first case, surface flashover paths when impulse voltage was superimposed on ac are shown in Fig. 2.

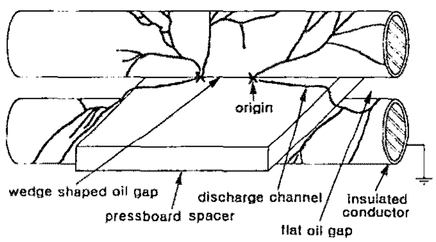
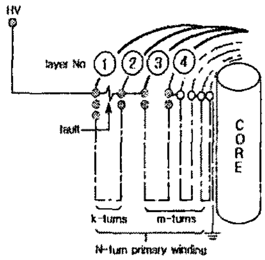


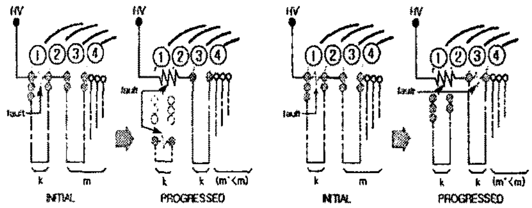
Fig. 2 Surface flashover paths under impulse voltage superimposed ac

As shown in Fig. 2, according to the experiment simulating the transformer conductors subjected to impulse voltages superimposed with ac, the discharge due to the surge mostly shows the surface flashover[6], and the discharge channels are originated from small oil wedge in pole transformer. Similarly to most of surface flashover, however, the breakdown due to the discharge channels does not inflict damage on the insulating materials. Generally, the follow current flowing through the channels formed by the surge voltage causes larger failures.

Fig. 3 shows the schematic for the short circuit analysis of pole transformer winding.



(a) Faulted primary winding



(b) Progressed to short circuit between turns (c) Progressed to short circuit between layers

Fig. 3 Short circuit analysis of pole transformer winding

As shown in Fig. 3(a), the faulted primary winding can be divided into 2 parts-the faulted turns(k turns) and the remaining turns(m turns) and analyzed as a 2 winding transformer. The unfaulted turns will be energized at the system voltage and act as a "secondary" winding with a turns ratio of m/k. The voltage induced in the shorted turns will be k/m times the primary or source voltage and the current in the shorted turns will be m/k times the primary current(ignoring the magnetizing current). The primary winding fault current will be limited by the leakage reactance between the faulted and unfaulted windings(not the same as the short circuit reactance) and the effective primary resistance.

Fig. 3(b) schematically describes the progression of a fault within initially faulted layer 1 and 2. The fault involving k shorted turns burns into the layers 1 and 2 bypassing some of the turns and reducing the number of shorted turns to k′/k.

Fig. 3(c) schematically describes the progression of a layer 1 to 2 fault to an adjacent layer-to-layer fault(layers 3 to 4). The involvement of the 3rd and 4th layer can occur without the original layers because the turns are simply burned off by the fault current. This type of progression is observed during transformer tear-down[5].

2.2.4 Ageing due to discharge

The ageing due to discharges is divided into the ageing due to arc with high temperature and the ageing due to partial discharges with chemical reaction. The heat generation due to arc is very high to be thermal depolymerization process, but in some cases, gases are produced at oxidative ageing as each atom and molecule generated by dissociation reacts ambient oxygen. In partial discharge ageing, it is oxidative ageing in principle, but the oxidative ageing is chemical reaction due to heat and ultraviolet, while the partial discharge ageing is governed by the direct collision of electrons with positive/negative ions electrons, atomic typed oxygen and activated oxygen.

2.3 Methods for failure cause analysis

2.3.1 macrography

This is to inspect the apparent defects by eyes, and it is very important item over all processes of failure cause analysis of pole transformers. Carbonization or discoloration of pole transformer components, melting due to arc, leakage of insulating oil, permeation of water, apparent deformation are observed.

2.3.2 mechanical tests

a. hygroscopic tests

This test is to examine the defect of ceramic stuff such as bushings. After crushing the bushings of interest, several splinters of the bushing is impregnated in dyestuffs(in a pressure cell) under high pressure. In specified time, the bushing is taken out of the cell and crushed again to smaller size to inspect the permeation of dyestuffs into the ceramic stuffs.

b. high pressure test

This test is to judge the sealing condition of the tank. For the test, the leakage of the oil is distinguished after the pole transformer is hung upside down for specified time, or the leakage of the compressed gas is judged after several [atm] of compressed gas is injected through the relief valve.

2.3.3 electrical tests

a. measurement of winding resistance

This is to understand whether the primary/secondary conductors are broken or not. In normal case, the resistance shows 10~30[Ω] between high voltage terminal and grounding terminal, and less than 1[Ω] between low voltage terminals, but in abnormal case, it becomes very high. In addition, the contact between primary and secondary is judged by measuring the resistance between high voltage terminal and low voltage terminals.

b. measurement of turn ratio

As needed, the turn ratio of the pole transformer can be taken by using turn ratio meter or by directly measuring the primary and secondary voltage.

c. other tests

Other tests but for the measurement of the resistance and turn ratio of windings - dielectric strength, relative permittivity, dissipation factor and specific resistance, etc.- are based on KS C 2105(Testing Methods for Electric Strength of Solid Insulating Materials) and KS C 2313(Testing methods of electrical insulating papers, pressboard and presspaper) in case of solid dielectric, and KS C 2101(Testing methods of electrical insulating oils) 및 KS C 2301(Electrical insulating oils) in case of liquid dielectric.

3. Flow for failure cause analysis of pole transformer

The failure factors mentioned above cause the secular ageing or shot time failure of pole transformers, with their unique mechanisms. General understanding of the flow to the failure is indispensable for analyzing the failure causes and devising proper countermeasures. Therefore, the flow of failure analysis is proposed based on the authors' experience and some foreign references.

Failure cause analysis flow is basically for 1 transformer and electrical and physical analysis is carried out from taking it over to complete disassembly.

Flowchart is shown in Fig. 4 based on the assumption above.

4. Conclusions

This paper sets forth guidelines for both the officials with KEPCO and pole transformer manufacturers, by analyzing the failure causes of pole transformers requested KEPRI and verifying the mechanisms to the failures. A study on the pole transformers has often been neglected despite that only exact analysis of the failure can prevent utilities from encountering similar failure again. In fact, the pole transformers are installed a lot in distribution systems, it is, however, not easy to find out the references dealing with exact analysis and proper countermeasures of pole transformers. The pole transformers are mounted closest to the customers, which gives direct damage when they fails. Therefore, the reliability of the power sully depends on the stable operation of the pole transformers. Various kinds of pole transformers manufactured by many domestic companies are installed in the distribution lines, failure aspects as many as possible have to be enumerated, but there are some restraints, the flowchart for failure cause analysis was constructed based on only the phenomena commonly observed in the failed pole transformers. The final purpose of this paper is to originally prevent the pole transformers from encountering failures, but it is very difficult. The failure aspects of pole transformers are far different from those of power transformers in some points, therefore, continuous studies have to be performed.

〔References〕

[1] H. Asai et al., Electrical Insulating Oil Handbook, Japan Petroleum Institute, February 1987

[2] Y. Ahang, X. Ding, Y. Liu and P.J. Griffin, "An Artificial Neural Network Approach to Transformer Fault Diagnosis", *IEEE Transactions on Power Delivery*, Vol. 11, No. 4, pp. 1836-1841, October 1996

[3] Y.T. Kim, T.K. Yang, I.K. Song and H.R. Noh, "A Trend of Varnish Impregnation Technology to Improve the Short Circuit Withstand Strength of Pole Transformers", Proceedings of KIEE, Vol. 49, No. 5, pp. 44-50, May 2000

[4] IEEE Transformers Committee, Dielectric Tests Subcommittee, Working Group on Revision of Dielectric Tests on Distribution Transformers and Task force Low-side Surge Requirements for Distribution Transformers, "Secondary(Low-side) Surges in Distribution Transformers-Task Force Report", *IEEE Transactions on Power Delivery*, Vol. 7, No. 2, pp. 746-756, April 1992

[5] J.M. Lunsford and T.J. Tobin, "Detection of and Protection for Internal Low-Current Winding Faults In Overhead Distribution Transformers", *IEEE Transactions on Power Delivery*, Vol. 12, No. 3, pp. 1241-1249, July 1997

[6] M.H. Park, Induction Machinery, Dongmyungsa, pp. 182-184, February 1969

[7] Liviu L. Alston, High Voltage Technology, Oxford University Press, pp. 129-140

[8] K.Y. Kim and Y.J. Yoon, "A Study on the Ageing Diagnosis of Insulating Oil for Pole Transformers using Spectrophotometry and Electroanalytical Chemistry", Electrical Engineering and Science Research Institute, pp. 21-27, September 1997

Fig. 4 Flowchart for failure cause analysis of pole transformer